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All-fiber photon-pair source at telecom wavelengths

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ABSTRACT

Single photon sources are a key element for quantum computing, quantum key distribution (QKD) and quantum communications. In particular, producing single photons at telecommunications wavelengths is valuable for QKD protocols and would enable realizing the quantum internet. The preferred method for their generation has long been spontaneous down conversion in bulk crystals, which suffers from connection loss to fiber networks. In-fiber spontaneous four-wave mixing provides a viable alternative as a photon pair source due to being compatible with existing fiber networks.

We present an all-fiber photon pair source based on degenerate four-wave mixing in a 400 m Highly-Nonlinear fiber, with signal and idler wavelengths generated at 1552.5 nm and 1557 nm respectively. The source consists of CW pump laser operating at 1554.75 nm, which is slightly detuned from the zero group velocity dispersion wavelength into the normal dispersion regime. After pair generation in the highly-nonlinear fiber, three arrayed waveguide gratings are employed to spatially separate signal and idler, and provides a 120 dB pump power reduction. Firstly the source is modelled and experimentally characterized in the well known classical regime of stimulated four-wave mixing. The effect of fiber cooling on spontaneous Raman scattering is modelled and characterized, and a 30% reduction in spontaneous emission is found when cooling the fiber to $-77\text{ }^{\circ}\text{C}$. In the low power regime the coincidence to accidental count ratio is simulated and measured. An increase in the coincidence to accidental count ratio is observed when cooling the fiber.

Keywords: Quantum optics, four-wave mixing, photon pair generation, quantum communication, quantum cryptography, fiber optics

1. INTRODUCTION

High brightness single photon sources are of increasing interest for use in quantum information sciences. Encoding information, transporting, and manipulating so-called qubits is essential for any real quantum computing or quantum communications network.¹ Especially photons generated at telecom wavelengths are of interest, since they have low loss in existing fiber optical network. Several approaches to generate single photons are being pursued. One avenue is deterministic sources such as atoms,² diamond defects³ and quantum dots.⁴ These are all based on driven two-level systems, often placed in a cavity to enhance interaction. In terms of quantum communication these systems suffer from low coupling efficiency to optical fiber, and often single photons are generated at visible wavelength, making them unsuitable for long-haul quantum communication due to the unaffordable loss at those wavelengths. Another approach to single photon generation is spontaneous generation of single photons pair-wise, using nonlinear effect such as spontaneous parametric down conversion^{5,6} or spontaneous four-wave mixing (SpFWM)^{7,8} These photon pairs are generated spontaneously, but timing information can be retrieved by detecting the idler photon, thereby heralding the signal photon. In-fiber SpFWM is an attractive solution for generating single photon pairs for quantum key distribution, since it is possible to generate pairs at telecom wavelengths, and the generated pairs are easily routed to existing optical fiber networks with low loss. The drawback of this method is accidental photons generated by broadband spontaneous Raman scattering (SpRS). In this paper the stimulated four-wave mixing is simulated and measured. The spontaneous Raman scattering spectrum is simulated using different coolants, and this compared to measurements. Lastly the coincidence to accidental ratio (CAR) is measured and compared to simulation.

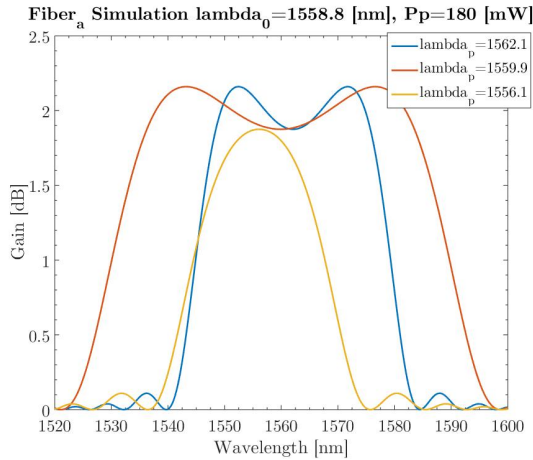


Figure 1. Simulated stimulated Four-wave mixing gain spectrum for the highly nonlinear fiber. With zero dispersion wavelength 1558.8 nm and Pump power 180 mW.

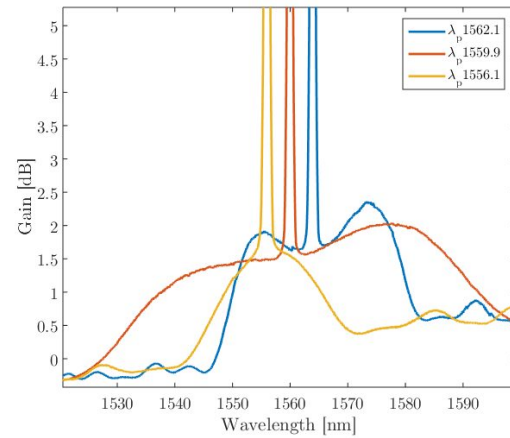


Figure 2. Measured stimulated Four-wave mixing gain spectrum at 180 mW pump power.

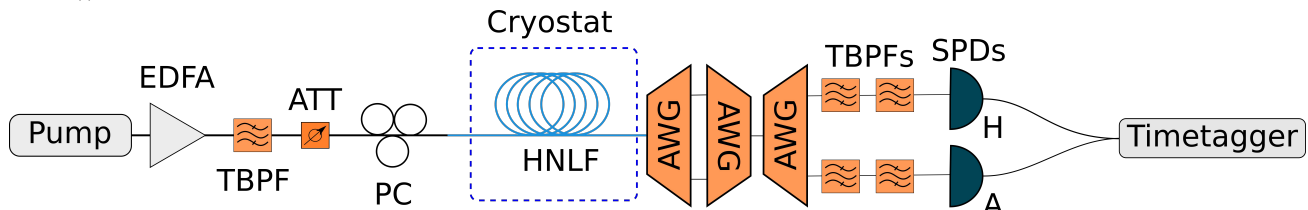


Figure 3. Setup for measuring coincidence to accidental counts. EDFA: Erbium doped fiber amplifier, TBPf: Tunable bandpass filter, ATT: Tunable attenuator, PC: Polarization controller, HNLf: Highly nonlinear fiber, AWG: Arrayed waveguide grating, SPD: Single Photon detectors.

2. STIMULATED FOUR-WAVE MIXING REGIME

To characterize the phase matching and the subsequent four-wave mixing gain spectrum of the Highly Nonlinear fiber (HNLf). The four-wave mixing is simulated using the dispersion parameters and non-linearity provided by the fiber manufacturer, and the parametric gain is calculated using⁹

$$G_s = \frac{P_s(L)}{P_s(0)} = 1 + \left[\frac{\gamma P_p}{g} \sinh(gL) \right], \quad (1)$$

where P_p is the pump power, γ the nonlinear coefficient, L the length of the fiber and $g^2 = -\Delta\beta[\frac{\Delta\beta}{4} + \gamma P_p]$ is the parametric gain, and $\Delta\beta$ the linear phase-mismatch. The stimulated four-wave mixing gain is then measured for three pump wavelengths: on the zero dispersion wavelength, in the anomalous dispersion regime, and in the normal dispersion regime. The simulated and measured gain spectra are seen on figures 1 and 2 respectively.

The gain bandwidth of the simulation corresponds well with the gain bandwidth of the measurements. Notice the pump at 1562.1 nm has the characteristic sidelobes of a pump in the anomalous dispersion both in the measurements and the simulation. For the gain measurement at 1556.1 nm, in the normal dispersion regime, they are no longer present. For the measured gain in figure 2 the gain asymmetric around the pump, this is likely due to Raman scattering. This effect is not included in the simulation in figure 1.

3. SIMULATION AND MEASUREMENT OF NOISE PHOTONS

In this section the different contributions to noise photons are analysed. There is a contribution from dark counts stemming from the intrinsic detectors noise, which is measured to be ≈ 50 Hz per detector. Furthermore, there is leakage of pump photons into the detectors either because of remaining side band photons from amplified

spontaneous emission, or due to lack of attenuation of the pump after having generated the photon pairs. The sideband photon are filtered by a tunable bandpass filter (TBPF) as seen in figure 3, and the remaining pump photons after the HLNF are filtered using a cascade of arrayed waveguide gratings (AWG), and TBPFs. The AWGs also serve to split the signal and idler photons. The remaining noise source are photons from SpRS which are managed using fiber cooling. To quantify how many of the photon counts in the idler channel originate from pump leakage, the photon count in the idler detector is measured with and without the fiber, with a 3 dB attenuator inserted to simulate the fiber loss. As seen on figure 4 the pump leakage is very low compared to the photons coming from nonlinear effects (which includes both SpFWM and SpRS) in the fiber.

In order to explore the effect of SpRS on our noise figure, the SpRS is simulated using that the SpRS photon flux is proportional to¹⁰

$$I_R \propto P_0 L |g_R| \mathcal{N} \quad (2)$$

where P_0 is the pump power, L the fiber length and $|g_R|$ is the Raman gain coefficient. \mathcal{N} describes the phonon contribution for the stokes and anti-stokes side and is given as¹¹

$$\mathcal{N} = \begin{cases} n(\Omega) & \Omega > 0, \\ n(\Omega) + 1 & \Omega < 0, \end{cases} \quad (3)$$

with $n(\Omega) = \frac{1}{\exp(\hbar|\Omega|/(k_B T)) - 1}$ being the phonon population at pump frequency detuning Ω and temperature T , with \hbar being the reduced planck constant and k_B Boltzmanns constant. The Raman gain coefficient can be calculated from¹⁰

$$g_R(\omega) = 2f_R \gamma \text{Im}[\tilde{h}_R(\omega)], \quad (4)$$

where $f_R = 0.18$ is the fractional contribution to the nonlinear polarization from the delayed Raman response, γ is the nonlinear coefficient and $\text{Im}[\tilde{h}_R(\omega)]$ is the imaginary part of the Raman response function which is modelled as described by Hollenbeck *et al.*¹² Using these equations the SpRS is simulated at different temperatures corresponding to having the fiber at room temperature (300 K), cooled by dry ice (200 K) and cooled with liquid nitrogen (77 K), as seen in figure 5. It is seen from the spectrum that the minimal Raman noise is found very close to the pump or more than 20 THz away. It is also seen that the fiber cooling is more effective on the anti-stokes side, and on the stokes side more effective the closer to the pump the photon pairs are generated. Close to the pump the reduction in SpRS is ≈ 30 % for cooling the fiber to 200 K compared to 300 K and an 80 % reduction when cooling to 77 K. Figure 6 shows the photon counts in the idler arm with the fiber at 300 K and 200 K. The reduction in counts corresponds to the 30 % expected from the simulation.

4. COINCIDENCE TO ACCIDENTAL RATIO

To characterize the source the coincidence to accidental ratio (CAR) is recorded at 300 K and 200 K. The CAR is calculated as

$$CAR = \frac{C - A}{A}, \quad (5)$$

where C is the raw coincidence counts and A the accidental coincidence counts. The coincidence counts are calculated from the peak in figure 7, and the accidental counts are the averaged background. This is compared to the simulated value for CAR, which is calculated in accordance with¹³ and¹⁴

$$CAR_{\text{sim}} \approx \frac{\eta_s \eta_i I_{\text{pair}} t_{\text{int}} \chi}{N_{\text{acc}}}, \quad (6)$$

where η_s is the signal side loss, and η_i is the idler side loss, t_{int} is the integration time, I_{pair} is the photon pair flux from the SpFWM, χ is the fraction of pairs within our coincidence window, and N_{acc} is the number of accidental coincidence counts, given by

$$N_{\text{acc}} = t_{\text{int}} t_{\text{win}} [\eta_i (I_{\text{pair}} + I_{R,i}) + r_{\text{dark}}] [\eta_s (I_{\text{pair}} + I_{R,s}) + r_{\text{dark}}], \quad (7)$$

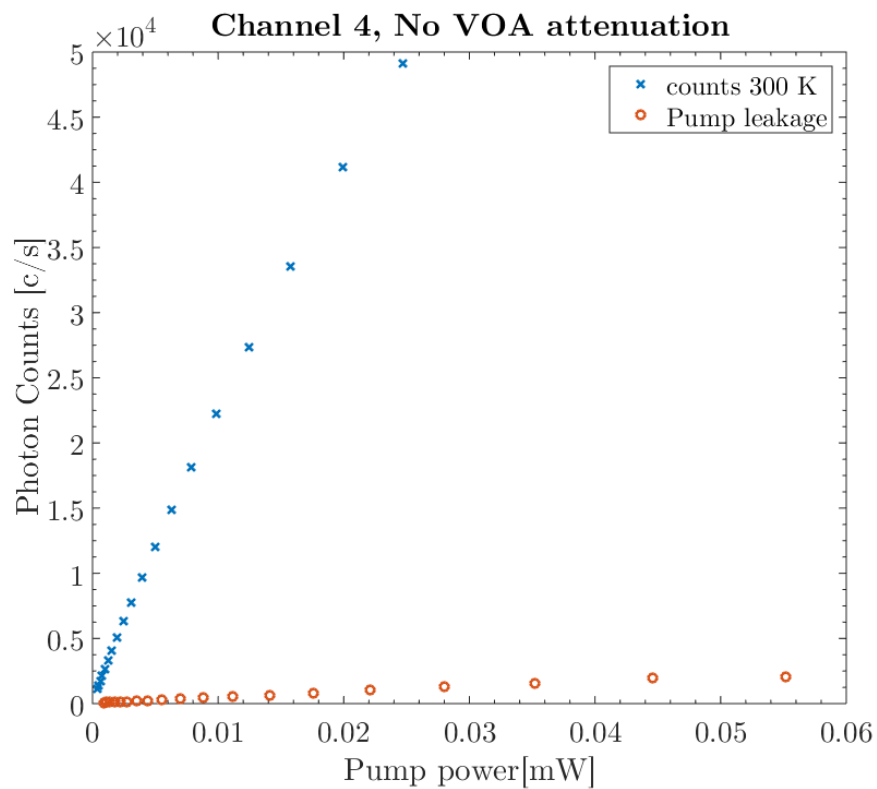


Figure 4. Photon counts from nonlinear effects and pump leakage.

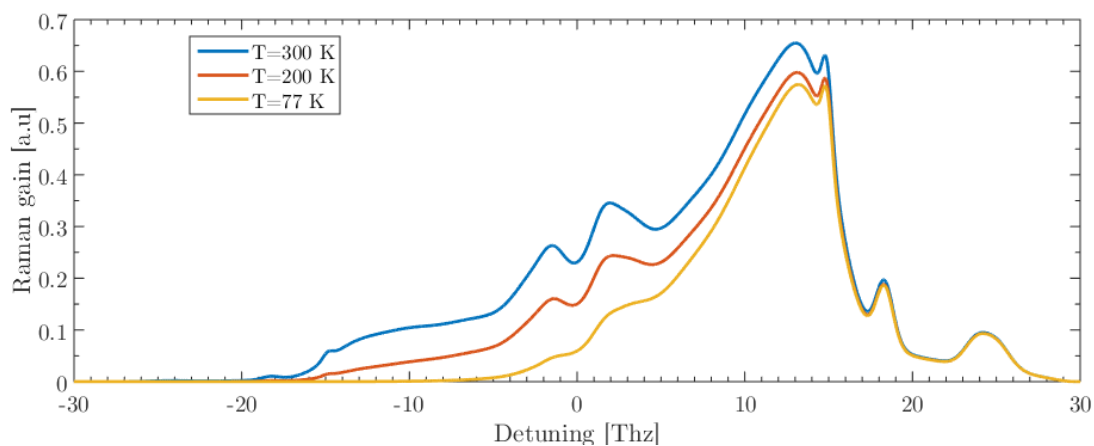


Figure 5. Spectrum of the spontaneous Raman scattering with negative pump detuning being the anti-stokes side and positive detuning being the stokes side.

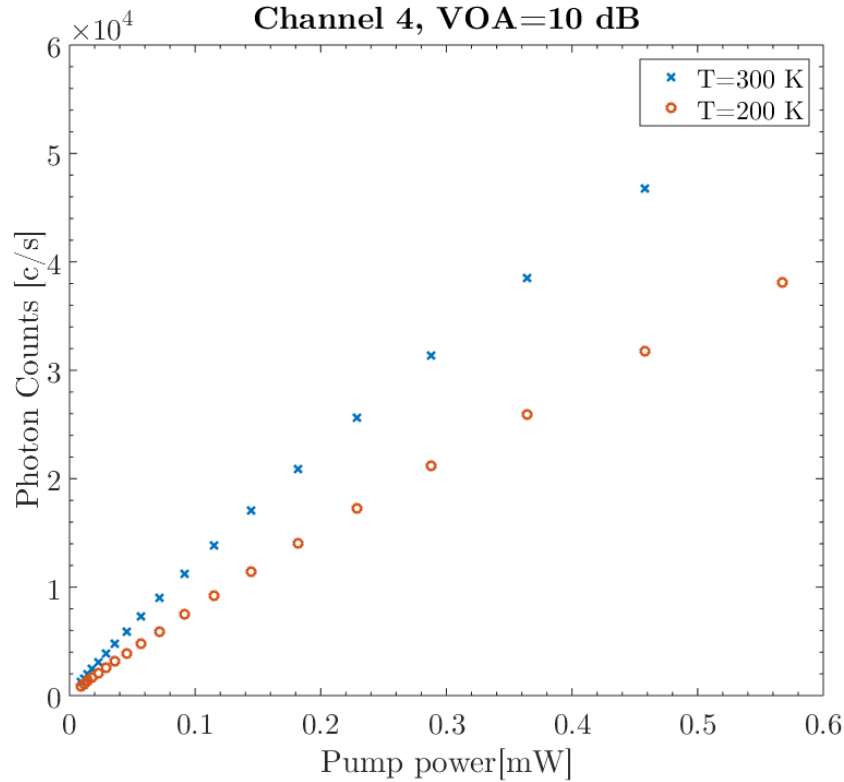


Figure 6. Idler side measurement of SpRS, for room temperature and cooled with dry ice.

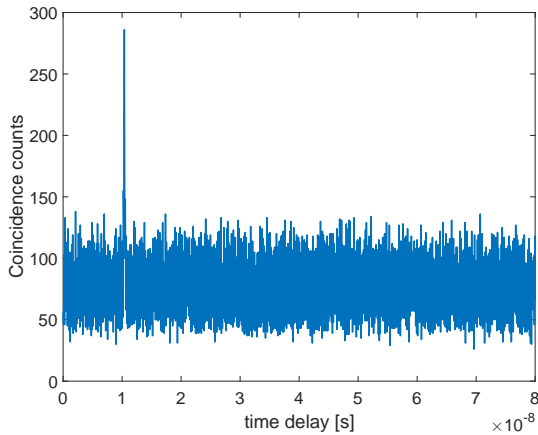


Figure 7. Coincidence histogram at $T = 200$ K and -3 dBm pump power

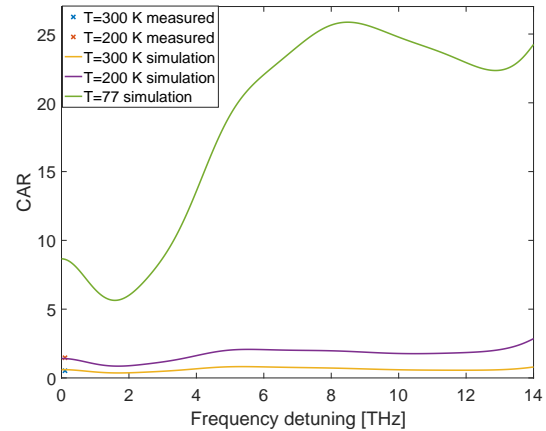


Figure 8. Simulated and measured CAR at -3 dBm pump power

where t_{win} is the coincidence window, r_{dark} the detector dark count rate, and $I_{R,u}$ is the SpRS photon flux where $u = i, s$ corresponding to the idler side (anti-stokes) and signal side (stokes) of the pump respectively. In the simulation perfect phase matching is assumed over all wavelengths, and a filter width of 0.7 nm is used. On figure 8 the CAR is plotted as a function of pump detuning, and the measured points are also shown. The measured CAR at $T = 300$ K is 0.52 and at $T = 200$ K it is 1.42, which corresponds with the simulated values. The value of the CAR is lower than the 10 needed to for QKD,¹⁵ but the expected CAR at 77 K is 8. It is seen that the CAR is optimal very close to the pump or when detuned more than 5 THz from the pump wavelength.

5. SUMMARY

The four-wave mixing and Spontaneous Raman scattering in the highly nonlinear fiber is simulated and experimentally characterized, and found to be consistent. The spontaneous Raman scattering spectrum is simulated and the photon flux is found to drop by 30 % when cooling the fiber to 200 K, in agreement with experiment. The drop in noise from SpRS results in an increase in coincidence to accidental ratio from 0.52 to 1.42. In the future cooling with nitrogen, or using higher order fiber modes to shift phasematching is expected to improve the noise figure significantly.

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